

A TRANSPORTABLE 50 KA DUAL MODE LIGHTNING SIMULATOR¹

K. Salisbury, S. Lloyd, Y.G. Chen
Maxwell Laboratories, Inc.

ABSTRACT

Maxwell Laboratories, Inc. has designed, built and tested a transportable lightning simulator capable of delivering more than 50 kA to an 8 μ H test object. The simulator was designed to be a versatile device in the lightning laboratory while meeting the requirements of MIL-STD-1757A for component E current waveforms. The system is capable of operating in either a ringing mode with a Q greater than 5 and a nominal frequency of 160 kHz, or a unipolar mode with no hardware configuration changes.

The ringing mode is obtained by the LCR series circuit formed by the pulse generator and test object. The unipolar mode is obtained by closing an electrically triggered crowbar switch at peak current. The simulator exceeds the peak current requirement and rate of rise requirements for MIL-STD-1757A in both the ringing and unipolar modes. The pulse half width in the unipolar mode is in excess of 50 μ s and the action is in excess of 10^5 A²s.

The design, component values, and test results are presented.

SYSTEM DESCRIPTION

The 50 kA Transportable Lightning Simulator is a complete turn-key lightning simulation system including the pulse power generator, system output diagnostics, control and auxiliary systems. The simulator is rugged and compact, for easy transportability, and provides a highly reproducible output pulse over a wide operating range. The ability to change the operating mode of the simulator without hardware changes at the

pulse generator is a key feature of this system that helps to maximize the operational availability of the system. A photograph of the simulator output connection and the control console is shown in Figure 1. A simplified block diagram of the system is shown in Figure 2.

The simulator provides peak current of more than 50 kA to an 8 μ H load, with either a damped sinusoidal or unipolar waveform. The system was specified to produce peak current and current rate-of-rise performance to meet MIL-STD-1757A Waveform E, shown in Figure 3. The generator was tested into an 8.05 μ H, 110 m Ω load at Maxwell Laboratories in San Diego in July 1990. Table I provides a listing of the demonstrated performance of the simulator, which meets or exceeds all customer specifications.

The simulator produces the damped sinusoidal waveform with an underdamped series RLC circuit consisting of the Marx generator and simulator inductance in series with the inductive load. This imposes a severe design constraint since the voltage across the crowbar switch and output bushing reverses to positive polarity and is present for a much longer time than in the crowbarred mode. The unipolar output pulse, with >50 μ s FWHM, is produced by closing a crowbar switch which shorts the simulator output terminal to ground at near peak current to provide an L/R decay time dominated by the load inductance as in previous lightning simulator systems^{2,3}. The modest voltage of the 50 kA simulator compared with full threat simulators³ allows the use of an electrically triggered SF₆ insulated crowbar switch. The 50 kA simulator can be changed from unipolar to ringing mode by simply disabling the crowbar trigger and overpressurizing the crowbar switch, with no reconfiguration of hardware in the pulse generator tank.

¹ This system was developed for Boeing Advanced Systems under contract number B239503.

² R. A. White, "Lightning Simulator Circuit Parameters and Performance for Severe-Threat, High-Action-Integral Testing," International Aerospace and Ground Conference on Lightning and Static Electricity, Orlando, FL, June 26-28, 1984.

³ J. L. Harrison, et al., "A Severe Threat-Level Lightning Simulator," International Aerospace and Ground Conference on Lightning and Static Electricity, Dayton, OH, June 24-26, 1986.

PULSE GENERATOR

The compact pulse power system is housed in a steel tank (110" l x 66" w x 80" h) insulated with one atmosphere (absolute) SF₆ gas. High voltage power supplies, trigger generators and auxiliary systems are located at the back wall of the tank, opposite the HV output. The generator is mounted on casters and weighs approximately 5000 lbs. The controls are mounted in a single rack that can be located up to 75 ft. from the generator.

A simplified circuit model of the 50 kA simulator is shown in Figure 4. The Marx generator is an 8 stage unit, with 2 plastic case 0.4 μ F capacitors per stage, arranged in a vertical column. The Marx stores about 18 kJ at full operational charge voltage. All Marx components are easily accessible for maintenance with charge and ground resistors mounted along the sides of the Marx and switches and trigger components mounted on the front. The Marx generator is assembled on an aluminum base plate and can be lifted from the pulse generator tank as a complete assembly.

The Marx generator is connected to the crowbar switch and output buswork through R_{series}, an assembly of 6 parallel water resistors. These protect the Marx generator in case of a short circuit fault and help damp out oscillations in the Marx/crowbar loop. The crowbar switch is located directly below the output buswork between the Marx and output bushing.

The crowbar switch is the same basic design as the laser triggered Sandia switch⁴, except for the addition of a midplane trigger electrode and a reduced main electrode gap spacing for the much lower voltage operation of the 50 kA simulator. The crowbar switch is SF₆ insulated, with a typical pressure of 48 psig for a 50 kA shot. The overall envelope of the crowbar switch housing is comparable to previous full threat simulators due to the SF₆ insulation of the pulse generator instead of oil, and the requirement for the crowbar switch to withstand the voltage waveform of the ringing output mode.

The crowbar switch is triggered from a small 6 stage Marx generator located inside an EMI shielded enclosure in the main pulse generator tank, shown in Figure 5. The crowbar switch trigger Marx is shielded to prevent crosstalk between the main Marx and trigger Marx when the main Marx generator erects. The crowbar switch trigger Marx is isolated from the crowbar midplane with an SF₆ insulated isolation switch, pressurized to hold off

the peak midplane voltage of about -250 kV and then close when the approximately -450 kV trigger pulse is applied.

The HV output connection of the pulse generator is insulated from the tank with a fiberglass reinforced polyester bushing mounted on the sloped front wall of the pulse generator tank. Connection rails on the front of the tank all around the output bushing allow the connection of wide planar current return conductors. This output configuration allows easy connection of the simulator to a wide variety of load configurations.

The output pulse is initiated when the Marx generator is triggered and the stored energy is transferred to the circuit inductors. Ideally the crowbar switch should close at peak current when there is no voltage across the switch. Previous laser triggered crowbar systems have operated with the crowbar switch closing somewhat past the current peak, when the voltage on the switch is increasing. The initial design for the 50 kA simulator was based on the crowbar voltage increasing to +100 kV before closing, which would give acceptable pulse width and ripple while easing the electrical triggering of the switch. In practice the crowbar switch triggered more easily than expected giving increased pulse width and reduced ripple compared to our baseline design.

EXPERIMENTAL RESULTS

System diagnostic monitors provided with the 50 kA pulse generator include an output voltage probe and a Marx current probe inside the pulse generator tank. The voltage probe is a water resistor voltage probe, connected between the output buswork and ground, which provides the voltage across the crowbar switch. The Marx current is monitored with a Pearson 301X current transformer in the ground leg of the Marx. B-dot probes are provided to monitor the trigger Marx and crowbar switch currents.

For the purpose of acceptance tests the 301X current probe and a Rogowski belt, cross calibrated to the Pearson current transformer, were installed outside the tank to measure the actual load current and load dI/dt. A Pearson 1049 probe was used to monitor Marx current during some acceptance test shots.

Data for a typical damped sinusoidal output pulse is shown in Figure 6, for a Marx charge voltage of 73 kV per stage. Load current and dI/dt are shown in Figure 6a,

⁴ M. J. Landry and W. P. Brigham, "UV Laser Triggering of Crowbars Used in the Sandia Lightning Simulator," International Aerospace and Ground Conference on Lightning and Static Electricity, Orlando, FL, June 26-28, 1984.

with a peak load current of 51.2 kA and a peak dI/dt of 5.3×10^{10} A/s. Figure 6b shows the Marx voltage (top) and current (bottom), with a peak output voltage of 452 kV. The oscillation frequency is 156 kHz with reversal of 75%. This full current ringing output mode is the most severe for the Marx generator and the Marx components are generously derated to provide high reliability, long life operation even under these harsh operating conditions.

Lifetime of the Marx capacitors is given approximately by the formula,

$$L_x = L_{REF} \left\{ \frac{V_x}{V_{REF}} \right\}^{-7.5} \left\{ \frac{Q_x}{Q_{REF}} \right\}^{-1.6} \quad (1)$$

The Marx capacitors have a design life $L_{REF} = 100,000$ shots at a reference voltage $V_{REF} = 85$ kV and $Q_{REF} = 0.976$. The full current ringing mode has values $V_x = 75$ kV and $Q_x = 5.5$ which gives an estimated Marx capacitor life of 18,730 shots. In actual operation many of the system shots will be at lower current or crowbarred, which will greatly extend the life of the capacitors. The Marx generator switches use tungsten-copper electrode material and have a design life of 10,000 shots at 100 kA and 0.5 C per shot, compared with the operation levels of 50 kA and 0.4 C per shot.

Typical unipolar output data is shown in Figure 7, for two different shots at 76 kV per stage charge. Figure 7a shows the Marx voltage and load current, Figure 7b shows the Marx current and load current. The peak voltage is -490 kV, with the voltage crossing through

zero and increasing to about +65 kV before the crowbar switch closes. The peak load currents in Figure 7 are 51 kA and 50 kA, with ripple of 7.6% and 6%.

For the crowbarred mode the Marx voltage reversal is only 13%, compared to 75% for the ringing mode. Therefore the expected life of the Marx capacitors is 336,000 shots for full current unipolar operation. The charge transfer through the Marx switches is reduced to 0.165 C, from 0.4 C for the ringing mode.

Figure 8 shows the load current at long time scale for a crowbarred shot at 30 kV per stage charge. Peak load current is 19.6 kA and an exponential decay time of 92 μ s. This gives crowbar switch charge transfer of 1.8 C and action integral of 1.77×10^3 A²s. The maximum charge transfer and action demonstrated for the system are 4.4 C and 1.1×10^5 A²s for a charge voltage of 76 kV per stage.

CONCLUSIONS

The 50 kA dual mode lightning simulator system described provides a versatile testing device for the lightning laboratory. The generator provides peak currents of more than 50 kA in a compact, lightweight system that is easily adapted to a wide variety of load configurations. The electrically triggered crowbar switch has proven to be reliable and effective, without the operational problems and safety hazards associated with laser triggered designs. The ability to change between two output modes with no hardware change provides maximum testing availability for the system.

Table I. Pulse Generator Electrical Performance

| PARAMETER | MAXWELL DEMONSTRATED PERFORMANCE |
|------------------------|--|
| Load | 8.05 μ H, 110 m Ω |
| Maximum Current | 51.2 kA |
| Minimum Current | |
| Ringing | <15 kA |
| Unipolar | <15 kA |
| Frequency (ringing) | 157 kHz |
| Pulse Width (unipolar) | 60 μ s |
| Circuit Q | 5.3 |
| Time to Current Peak | 1.52 μ s |
| Current Rate of Rise | >5 $\times 10^{10}$ A/s for >0.3 μ s >2.5 $\times 10^{10}$ A/s for >1 μ s |
| Ripple | 7.7% |
| Peak Current Variation | <4.6% |
| Action | 1.1 $\times 10^5$ A ² -s |
| Pulse Repetition Rate | ≥ 1 Pulse Every 2 Minutes for 5 Pulses |

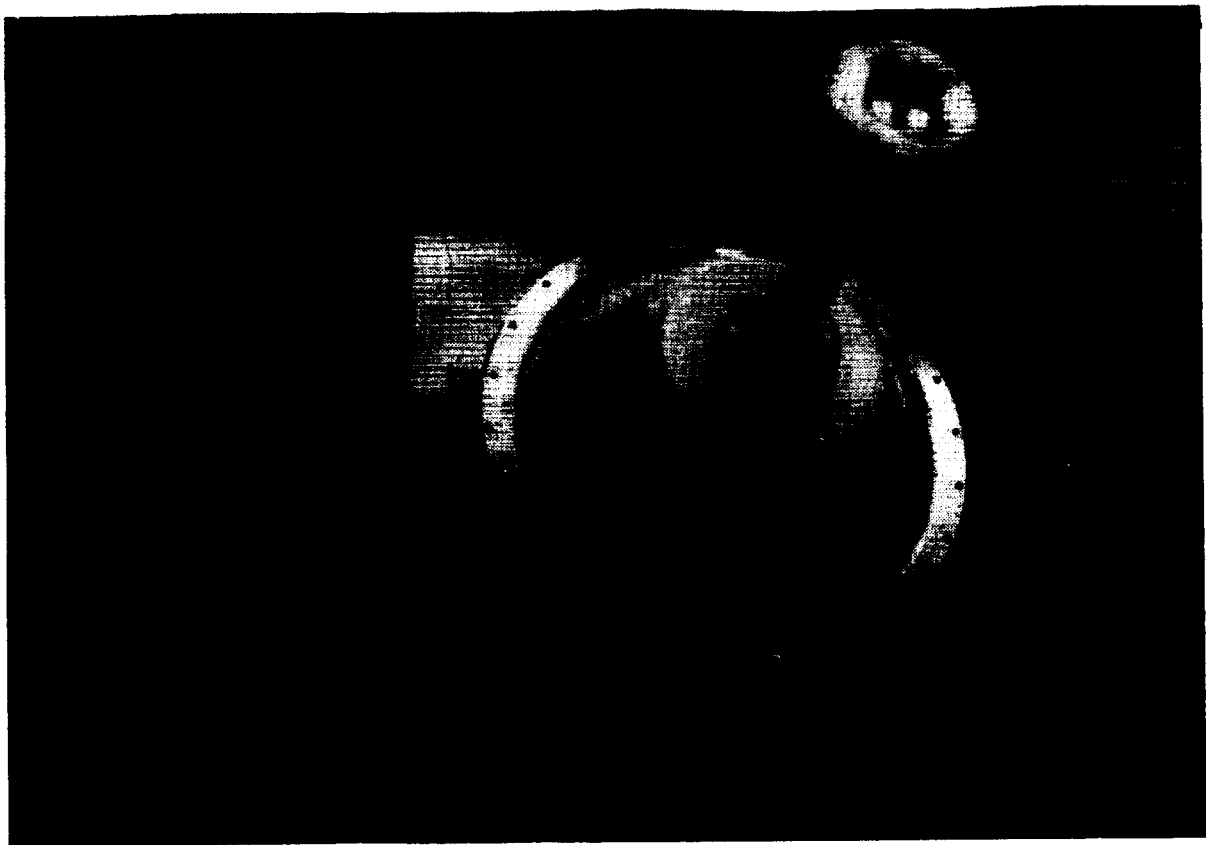
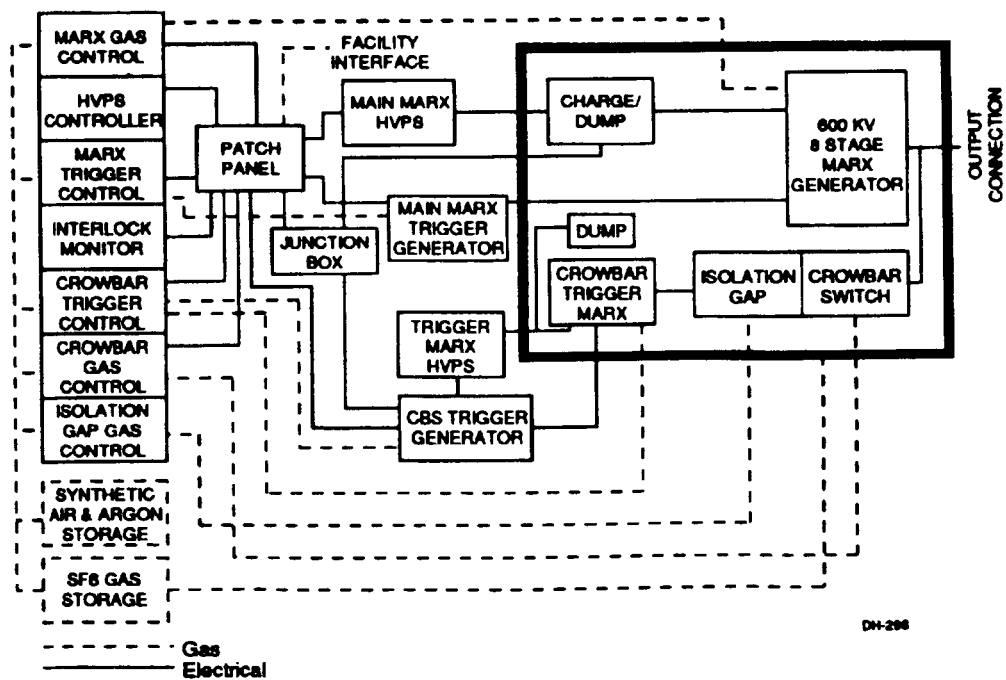


Fig. 1 - Output section and control console of the 50 kA lightning simulator



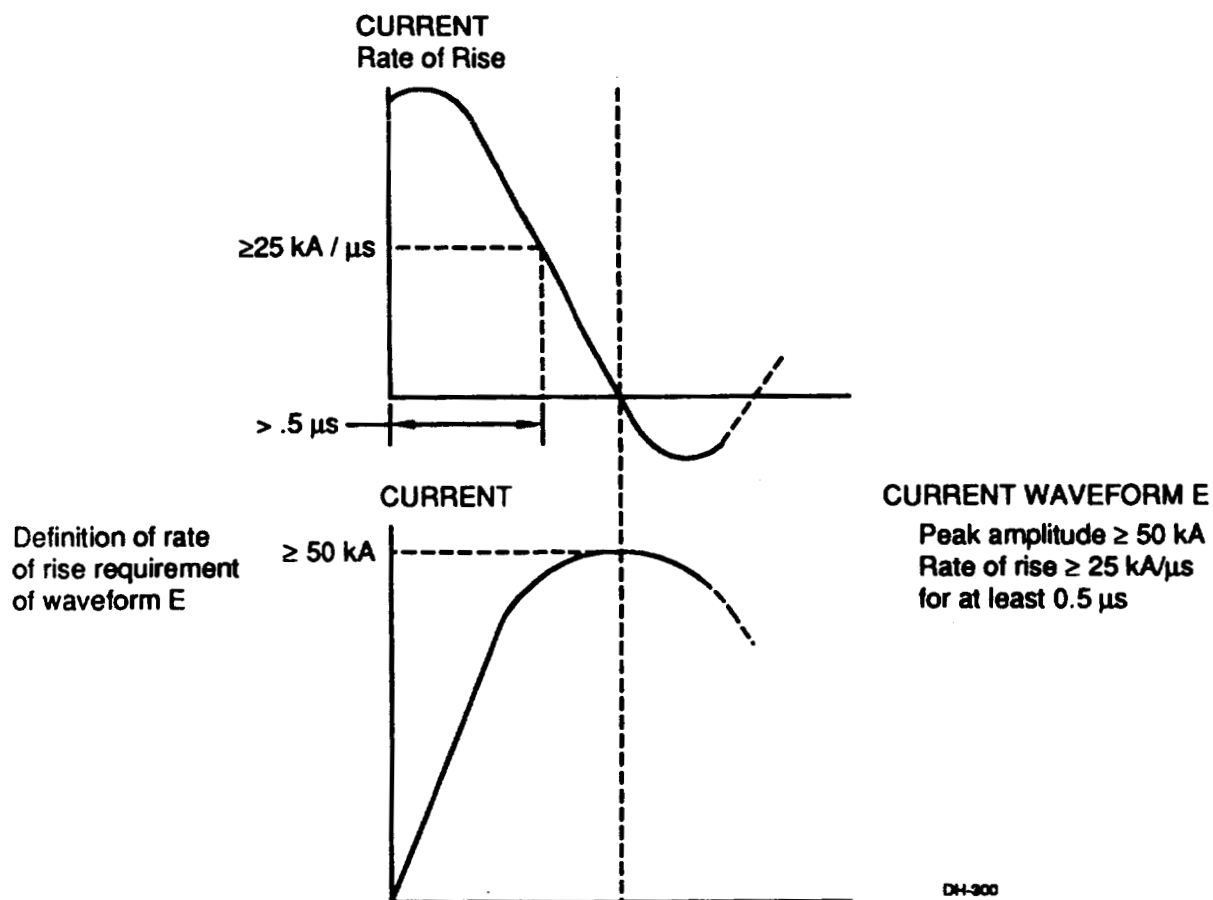


Fig. 3. - MIL-STD-1757A Current waveform E requirements

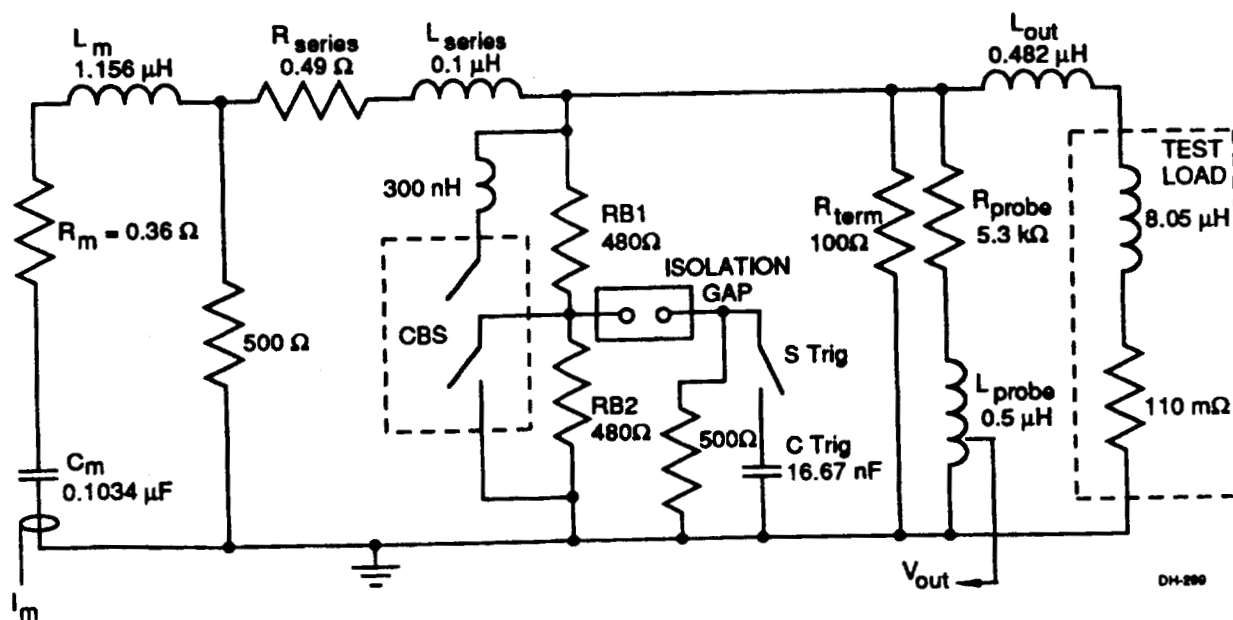


Fig. 4 - Simplified circuit diagram

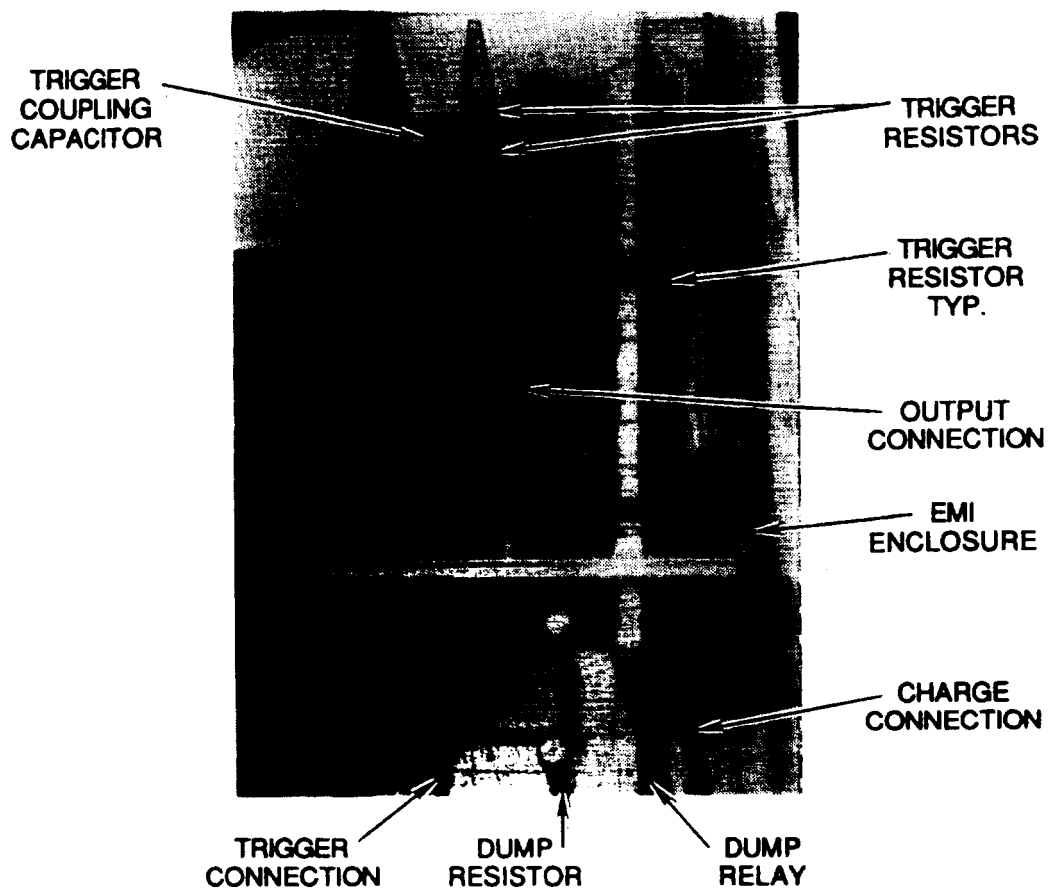
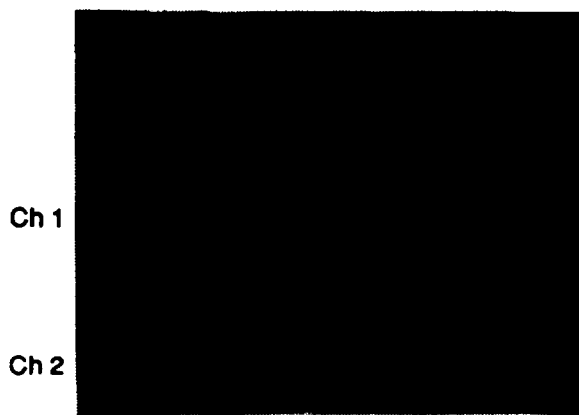
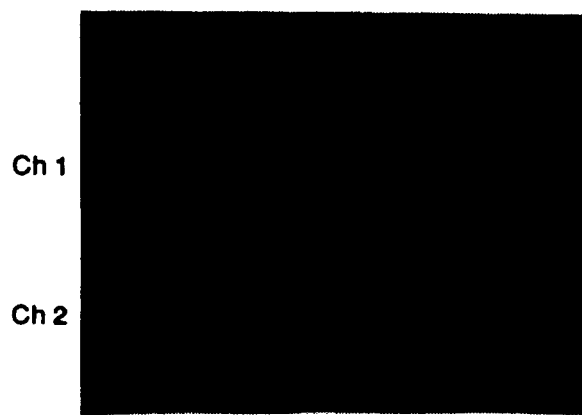


Fig. 5 - Marx generator



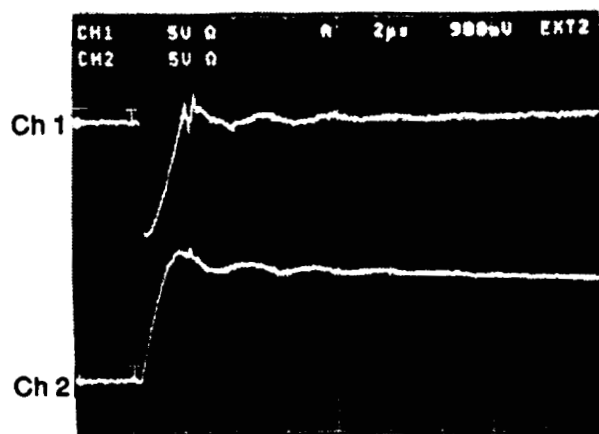
(A) Ch 1 - I_L (22.95 kA/Div)
Ch 2 - I_{Load} (16.83×10^{10} A/s/Div)



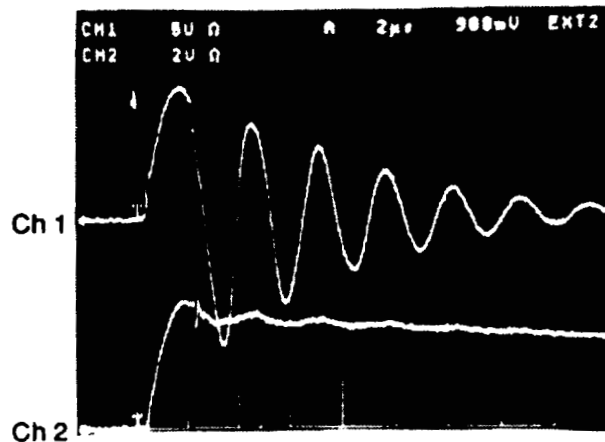
(B) Ch 1 - V_{Marx} (211.25 kV/Div)
Ch 2 - I_{Marx} (25 kA/Div)

Fig. 6 - Typical damped sinusoidal output pulse

CONTROL PANEL
REPAIR OUTLET

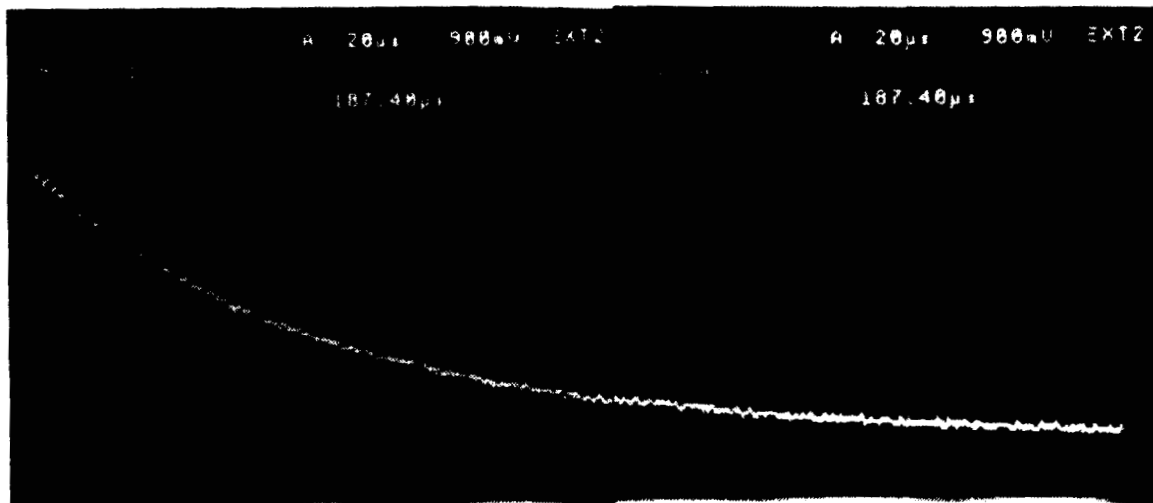


(A) Ch 1 - V_{Marx} (225 kV/Div)
Ch 2 - I_L (20.4 kA/Div)



(B) Ch 1 - I_{Marx} (20 kA/Div)
Ch 2 - I_L (20 kA/Div)

Fig. 7 - Typical unipolar output pulse



4.08 kA/Div

Fig. 8 - Load current

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